HOW GOOD ARE THE PREDICTIONS FOR OSCILLATION FREQUENCIES?

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Abstract. We have used available intermediate degree p-mode frequencies for the solar cycle 23 to check the validity of previously derived empirical relations for frequency shifts (Jain *et al.*: 2000, *Solar Phys.* **192**, 487). We find that the calculated and observed frequency shifts during the rising phase of the cycle 23 are in good agreement. The observed frequency shift from minimum to maximum of this cycle as calculated from MDI frequency data sets is 251 ± 7 nHz and from GONG data is 238 ± 11 nHz. These values are in close agreement with the empirically predicted value of 271 ± 22 nHz.

1. Introduction

An understanding of the physical processes responsible for the changes in the solar p-mode frequencies could provide an important clue to the inner workings of the solar activity cycle. It is now well established that these frequencies change with time (Woodard and Noyes, 1985) and show a positive correlation with activity indices (Woodard *et al.*, 1991; Bachmann and Brown, 1993). Over the last two decades, attempts have been made to precisely measure the changes in p-mode oscillation frequencies. More recently, with the Global Oscillation Network Group (GONG) (Harvey *et al.*, 1996) and Michelson Doppler Imager (MDI) on board Solar and Heliospheric Observatory (Scherrer *et al.*, 1995) instruments, the measurements are made consistently with an accuracy of one part in 10^5 or better. These continuous data sets further confirm that the oscillation frequencies are well correlated with the activity indices (Jain, Tripathy, and Bhatnagar, 2000 and *references therein*). Following a different approach and using a data set of eight years between 1981 and 1989, Rhodes *et al.* (1993) reported that the frequency shifts are also correlated with the change in various activity indicators. This study was extended to the rising part of the cycle 23 by Jain *et al.* (2000; hereafter JTBK). Using the GONG frequencies for the period May 1995 to October 1998, they confirmed that the frequency shifts are better correlated with the change in activity indices. In an attempt to quantify the changes in mode frequencies, JTBK derived empirical relations between the shift in frequencies and change in the level of activity indices and showed that these relations do not change

significantly from cycle to cycle. Using a limited data set from GONG network for the ascending part of the current cycle 23, it was found that the calculated and observed frequency shifts were in close agreement.

The motivation of this paper is to check the validity of the derived relations for the maximum and descending phase of the current solar cycle. This is accomplished by determining the frequency shifts using the smoothed sunspot number and equation (8) of JTBK. The calculated shifts are compared with the measured shifts obtained from recent observations. We find that the calculated and observed frequency shifts are in close agreement confirming that the derived relations can be reliably used to estimate the *p*-mode frequencies for past, present and future solar activity cycles, if the solar acitivity index is known.

2. Frequency Data Sets

In order to check the validity of emprical relations of JTBK, we have used intermediate degree *p*-mode frequencies for the solar cycle 23 from GONG and MDI instruments covering a period of more than five years. The GONG data consist of fifty three, 108 day overlapping data sets starting from 7 May 1995 to 6 October, 2000. This covers the declining phase of the solar cycle 22 and the rising phase of the solar cycle 23. The MDI data consist of twenty four, 72 day data sets and cover the period from 1 May, 1996 to 15 June, 2001 with two breakdowns in between. Since empirical relations of JTBK are valid in the spherical harmonic degree range $5 \leq \ell \leq 99$ and frequency range 1500 μHz $\leq \nu \leq$ 3500 μHz, we have considered only those common modes which lie in between these two ranges. This selection criterion generated a total number of 327 common modes for GONG data and 651 modes for MDI data.

3. Results and Discussion

We estimate the change in *p*-mode frequencies for solar cycle 23 using the equation (8) of JTBK:

$$\delta\nu \;=\; (2.41 \pm 0.19)\;\delta R_s - (0.48 \pm 1.68), \tag{1}$$

where $\delta\nu$ is given in nHz and δR_s is the change in smoothed sunspot number. The variation of sunspot number taken from the *Solar Geophysical Data* web page for the observing period of MDI is shown in Figure 1. The estimated frequency shifts obtained from Equation (1)

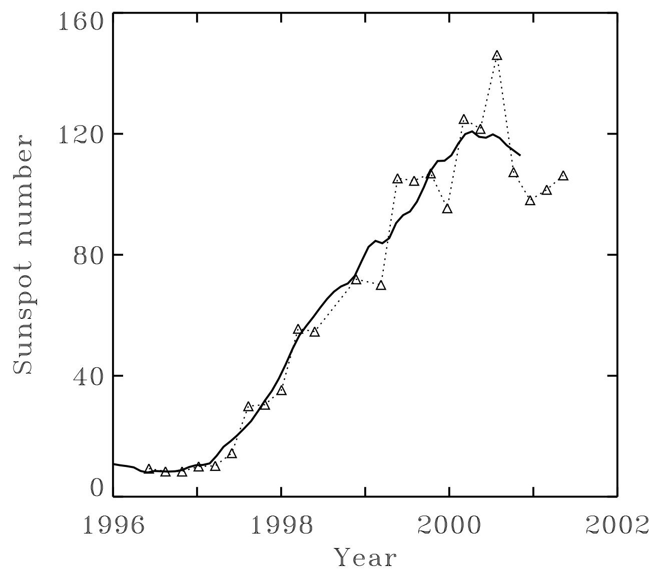

Figure 1. The smoothed sunspot number (solid line) and mean international sunspot number (triangles) averaged over each of twenty-four, 72-d observing periods of MDI.

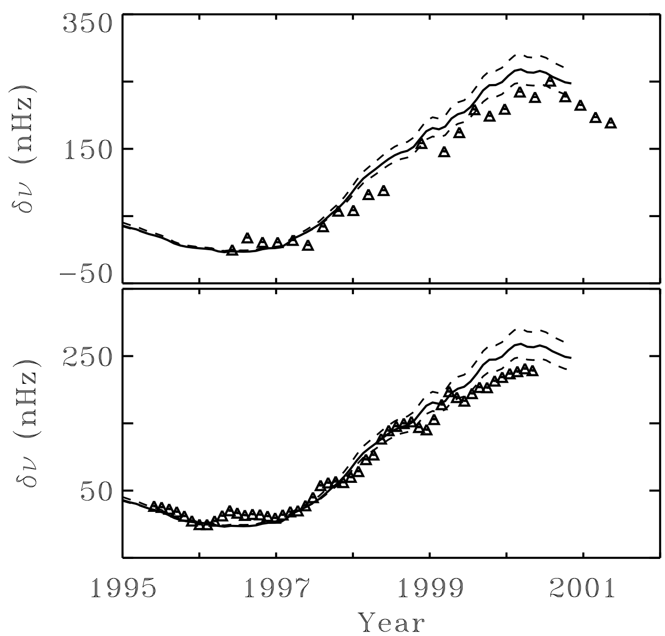

Figure 2. The calculated (solid line) and observed (triangles) frequency shifts for 1995-2000. The lower panel shows the variation in GONG frequencies and upper panel for MDI frequencies. The 1 σ errors are shown by dashed lines.

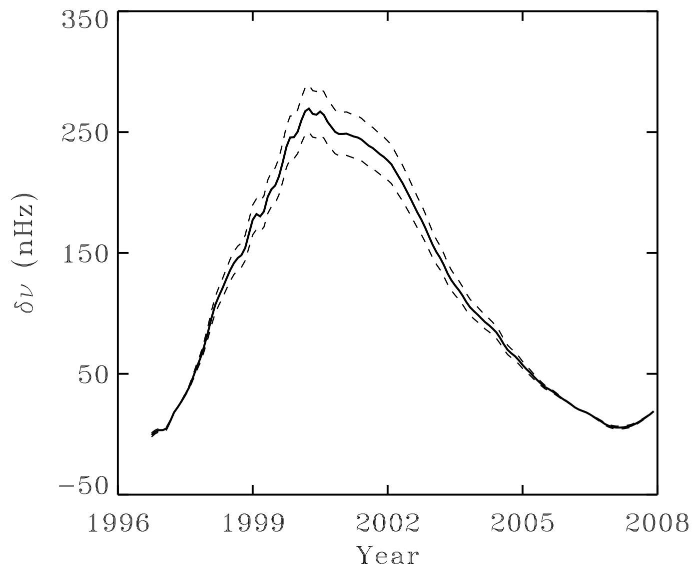

Figure 3. The estimated frequency shifts for the solar cycle 23 using predicted sunspot numbers. The dashed lines represent the errors in the calculation due to the errors in predicted activity index.

are plotted in Figure 2 for the period from January, 1995 to December, 2000. The measured shifts for both GONG (lower panel) and MDI (upper panel) data sets are also plotted in the same figure and shows that the observed frequency shifts are in close agreement with those obtained from the empirical relation. During the ascending phase, the GONG frequency shifts agree better with the derived shifts while the frequency shifts of MDI data sets are in close agreement during the maximum phase of the cycle. On an average, we find that the deviation between the calculated and observed frequency shifts is within 1σ error level.

Quantitatively, the derived shift between the minimum and maximum of the current solar cycle amounts to 271 ± 22 nHz corresponding to the maximum smoothed sunspot number of 120.8. This can be compared to the observed shifts of 251 ± 7 nHz for MDI and 238 ± 11 nHz for GONG data and clearly shows a discrepancy near the maximum phase of the cycle indicating to the complex nature of the relationship that may exist between activity index and the frequecy shift. Earlier, JTBK had quoted a maximum shift of 265 ± 90 nHz corresponding to the predicted maximum sunspot number of 118 ± 35.

The estimated frequency shifts for the complete solar cycle 23 (1996 - 2008) are plotted in Figure 3. The solid line represents the estimated shifts calculated using the predicted smoothed sunspot number taken

from the *Solar Geophysical Data* web page and dashed lines are the predicted 1σ error.

In summary, we have used available intermediate degree p-mode frequencies from GONG and MDI projects for the solar cycle 23 to check the validity of previously derived empirical relations for frequency shifts (Jain *et al.*, 2000). We find that the calculated frequency shifts are in close agreement with the observed shifts during the period considered in this analysis which includes the rising phase of the cycle 23. We conclude that the empirical relations as derivd by JTBK can be considered as good predictors of frequency shifts for solar activity cycles.

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